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Large eddy simulation of flow over inclined wavy cylinders

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A B S T R A C T

The wavy cylinders have been proven effective in suppressing the Kármán vortex shedding and mitigating the aerodynamic forces. As yet their performance in the inclined incoming flow has not been well understood. In the current work, large eddy simulations are carried out to unveil the aerodynamics of the flow around inclined wavy cylinders at the Reynolds number of 5000. Three inclination angles, 0°, 30° and 45°, together with 2×2 combinations of shape parameters, namely $\lambda/D_m = 2$ and 6, $a/D_m = 0.1$ and 0.15, have been taken into consideration. Firstly, the aerodynamic force coefficients in terms of both the span-wise averaged and sectional values are discussed at length. It is revealed that the growing inclination angle invites not only a surge in their span-wise averaged values, but also an enlargement in the sectional difference of the force coefficients. The span-wise correlation of the lift force is found to be enhanced for the wavy cylinders with the increase of inclination angle, while the opposite is true for the normal cylinders. By examining the mean wake properties, it is disclosed that the increase in the span-wise averaged drag force coefficients is closely related to the shrinkage in the vortex formation length and the regression of the base pressure, whereas the sectional distribution of the drag coefficients is largely affected by the stagnation pressure. The mean wall shear stress fields are exploited to shed light on the flow topology of the cylinder surfaces. It is discovered that the wavy cylinders, especially the short-wavelength one, exhibit significant span-wise variation in the separation structure in the inclined flow. Besides, the chaotic surface flow in the rear side of the non-inclined cylinders could be regulated to maintain symmetry by the secondary axial flow in the near wake of the inclined cylinders. The instantaneous three-dimensional vortical structures are visualized by the Q isosurfaces at last to collaborate the previous discussions. A preliminary mechanism for the cessation of flow control efficacy for the wavy cylinders in inclined flow is also presented.

1. Introduction

Bluff bodies, such as circular cylinders submerged in the air or water are often plagued by the excessive fluid-induced forces and vibrations. For example, as the span of the cable-stayed bridges grows longer, the wind loads on the cables tend to become larger than that on the girder. This increases the construction cost of the other bridge members such as the towers (Hojo et al., 2000). In the case of ocean mining, the vortex induced vibration of the deep-sea risers causes constant

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concern of fatigue failure. A lot of efforts have been devoted the manipulation of the flow behind the bluff structures and some have been employed in the practical engineering applications (Kumar et al., 2008) with varying degree of success. Still, the discipline of flow control remains active and patenting.

Lately, the 3D forcing flow manipulation technique (Choi et al., 2008), which applies varying controls along the spanwise direction of bluff bodies such as circular cylinders, has been recognized effective in controlling the flow behind bluff bodies. Typical approaches pertaining to this technique include passive means such as helical strakes (Zdravkovich, 1981), small tabs (Park et al., 2006), and active open-loop controls such as distributed blowing and sucking (Kim and Choi, 2005). The latter, especially, has been found to be of high efficiency. Furthermore, it is revealed by Hwang et al. (2013) that the spanwise waviness, as is actively engendered in Kim's case (Kim and Choi, 2005), greatly stabilizes the global instability in the cylinder wakes, and should be applicable to most 2-dimensional bluff bodies.

The aforementioned flow control mechanism could also be realized by the wavy cylinders, i.e., straight axis with sinusoidally varying diameter, as is depicted in Fig. 1. Such a geometry has firstly been examined by Ahmed and Bays-Muchmore (1992), who found out that significant pressure gradient exists in the spanwise direction, resulting in greater sectional drag coefficients at the geometric nodes than the saddles. Ahmed et al. (1993) looked further into the turbulent wake of the wavy cylinder geometry and revealed the three-dimensional development of the mean and turbulent structures in the wake. The research group led by Lam has also been active in this topic. By joining experimental and numerical approaches, they have shown that the wavy cylinders excel at flow control and force reduction (Lam et al., 2004a, b), and with optimized shape parameters, the Kármán vortices could even be completely suppressed (Lam and Lin, 2009). The relationship between the shape parameters and the flow control efficacy was also established at low Reynolds numbers in Lam and Lin (2009). Wavelength was found to play a dominant role in deciding whether the cylinder is control-effective and the amplitude affects the extent of the reduction. In particular, two optimal wavelengths, i.e., $\lambda/D \approx 2.5$ and 6, have been identified at $Re = 100$ to yield maximum drag and lift mitigation. The same paper also reported that the optimal shape parameter for the most effective flow control depends highly on the Reynolds numbers, at least in the range of 60–150. At higher Reynolds numbers, where the wake flow is inherently turbulent, satisfactory flow control efficacy could be maintained over a large range of Re if wavy cylinders are design with $\lambda/D \approx 2$ (Zhang et al., 2005; Lee and Nguyen, 2007; Xu et al., 2010; Jung and Yoon, 2014; Wang and Liu, 2016), as well as $\lambda/D \approx 6$ (Lam et al., 2010b, a; Lin et al., 2016). Application-wise, Kleissl and Georgakis (2011) and Zhang et al. (2016) investigated the aerodynamics of the wavy cylinder as potential bridge cable models. Wu et al. (2013) proposed to use the pod-like wavy coating for the deep sea risers to reduce the vortex induced vibrations. Moreover, this undulated geometry is found to resemble the shape of the harbor seal's whiskers, which is believed to have enhanced sensitivity (Hanke et al., 2010) in the turbid water. This finding has led to the bio-mimicry innovations like the energy conserving flow sensors (Beem et al., 2012).

It is common occurrence that the natural flow attacks the structures from all possible angles. Considerable efforts have been devoted to the flow around an inclined normal circular cylinder. By theoretical developments Sears (1948) studied the flow past a yawed cylinder and revealed that the axial dimension could be removed from the boundary layer governing equations since it is uncoupled to the other two dimensions. This indicates the famous independence principle (also referred to as the cosine rule) that the aerodynamics of the flow around an inclined cylinder could be evaluated by the velocity component that is normal to the cylinder axis. However, Sear's theory has been limited to the boundary layer region and its direct application to the whole flow could not be assured. Thanks to the large body of experimental works on this topic (Hanson, 1966; Hoerner, 1965; Surry and Surry, 1967; Kozakiewicz et al., 1995; Marshall, 2003; Zhou et al., 2009; Van Atta, 1968; Ramberg, 1983), it is now acknowledged that the validity of the independence principle could be expected as long as the inclination angle α is smaller than $40°$–$50°$, where α is defined as the angle between the velocity vector itself and its component perpendicular to the cylinder axis. It is also revealed by Ramberg (1983) that the wake flow of the inclined cylinder has a high sensitivity to the upstream boundary condition, especially at low Reynolds numbers. It could be imagined that by the axial component of the flow velocity as well as the secondary axial flow generated in the wake (Matsumoto et al., 1990), the disturbances incurred by the upstream end condition could contaminate the entire wake flow. The effect of the cylinder end condition has also been studied in several numerical works, such as Kawamura and Hayashi (1994) and Yeo and Jones (2008), who both stressed the significant influence of the boundary condition to the wake flow. For this reason, most of the numerical works on the inclined cylinder have employed the cyclic boundary condition for the two span-wise ends in order to mimic an infinitely long cylinder (Lam et al., 2010b; Yeo and Jones, 2008; Bourguet et al., 2015; Bourguet and Triantafyllou, 2016; Lucor and Karniadakis, 2003). This boundary condition is also adopted in the current paper.

Despite the omni-directionality of the wavy cylinder in its cross-sectional plane, the existence of the spanwise wavy tubercles adds complexity to the cross flow if the cylinder axis is not perpendicular to the incoming flow. The flow past an inclined wavy cylinder has been less studied. The only reference on this aspect is the work of Lam et al. (2010b). It was found out that although the mean drag and the fluctuating lift coefficients of a yawed wavy cylinder are less than those of a correspondingly yawed circular cylinder at the same flow condition, the independence principle is not no longer suitable for the inclined wavy cylinders, and with the increase of the yaw angle, the advantageous effect of wavy cylinder on force mitigation becomes insignificant. However, their discussion was limited to only one wavy shape, which makes it difficult to form a conclusive view on the current topic.

Following the above literature, the current work endeavors to further enhance the understanding towards the aerodynamics of the wavy cylinders, especially the ones inclined to the freestream. Specifically, we numerically investigate the wakes of wavy cylinders with different shape parameters subjected to both normal and inclined inflow. Various aspects,